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Tapered Yb^{3+}-doped photonic crystal fiber for blue-enhanced supercontinuum generation

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ABSTRACT

The absorption spectrum of the Yb^{3+}-doped photonic crystal fiber covers from 770 nm to 980 nm. A less flatness broadband continuous spectrum and a short peak are generated in the uniform Yb^{3+}-doped photonic crystal fiber. Supercontinuum from 388 nm to 1590 nm is received in the tapered Yb^{3+}-doped photonic crystal fiber, which covers almost two octaves, generating an ultra flat (7 dB) continuous spectrum coming from 926 nm to 1554 nm in the long waveband, and receiving a 62 nm width, high and violet peak from 388 nm to 450 nm in the purple waveband by femtosecond pulse. The up conversion efficiency of pump power in tapered Yb^{3+}-doped photonic crystal fiber is up to 59.4%, while the uniform is only 6.3%.

1. Introduction

The visible part of the ultrafast electromagnetic spectrum (350–800 nm) has a wide range of applications, including the optical coherence tomography [1], fluorescence resonance energy transfer [2], fluorescence lifetime imaging microscopy [3], high-precision calibration of astronomical spectrographs [4], and so on. This requires that the energy move to the visible part as much as possible when the supercontinuum (SC) generates. Traditionally, the nonlinear factors such as self phase modulation (SPM), stimulated Raman scattering (SRS), four wave mixing (FWM), cross phase modulation (XPM), soliton self-frequency shift (SSFS) and modulation instability (MI) work on together to broaden the spectrum from a few nanometers to hundreds of nanometers, even to thousands of nanometers. In order to improve the nonlinear of medium [5–7], which has no endless single mode, controllable dispersion, highly nonlinear and highly birefringence characteristics, the photonic crystal fiber (PCF) based on silicon appears, making the generation of broadband and flatness SC easier. A broad band (800–2500 nm) is generated in hexagonal-lattice PCF with 2 cm long pumped by a low pump pulse energy (35-nJ, 150-fs pulses at 1560 nm) [8]. In order to overcome the problem of low pump transfer efficiency, Wadsworth et al. [9] proposed to dope earth ions in core, which achieves highly pump transfer efficiency by stimulated emission of radiation. The energy level of Yb^{3+} is simple, the absorption is in excited state, the absorption band is wide, the emission cross-section is big and the fluorescence lifetime is long compared to other earth ions [10,11]. Therefore, SC generation in Yb^{3+}-doped PCF provides one of the most effective ways to achieve high optical wavelength conversion efficiency and broaden the spectrum and raise the flatness. Tapering is a kind of important after treatment technology of fiber. Through the process of "fast and cold", the zero dispersion wavelength (ZDW) shifts to blue and the nonlinear coefficient is improved while keeping d/Λ unchanged [12]. Tapering of PCF has proven to be an effective way to enhance the short wavelength edge of SC blue shift to the deep-blue, eventually the

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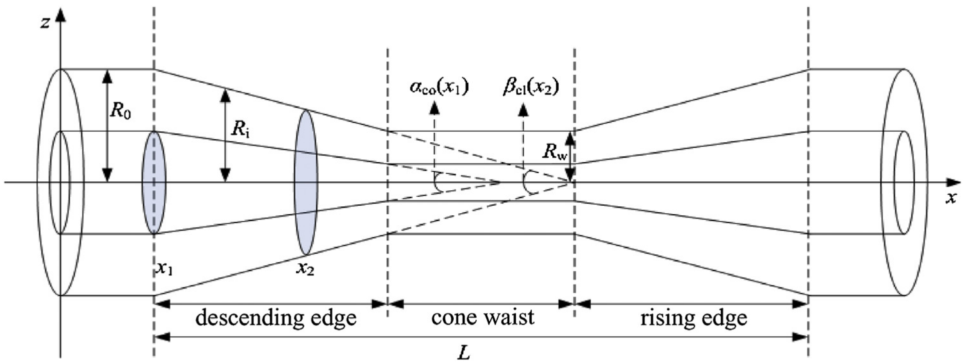

Fig. 1. Linear melting preparation tapered PCF cone structure.

ultraviolet [13–15]. Optimizing the parameters for achieving deeper blue components by group-index matching, Debashri Ghosh et al explore the extent of applicability of the group-index matching technique for obtaining blue-enhanced SC and finally optimize the location of the zero dispersion wavelength with respect to the pump wavelength to achieve the maximum blue shift [16]. By introducing giant chirp to the seed pulses and optimizing the pump power in every stage of the master oscillator power amplifier, a supercontinuum with 30.6 W output average power and an extremely wide spectrum of 385 nm to beyond 2400 nm is obtained [17].

In this paper, a tapered Yb^{3+}-doped PCF fabricated by “fast and cold” is present. It can make the ZDW shift to blue and increase the nonlinear interaction. The ZDW of uniform and tapered waist Yb^{3+}-doped PCF are calculated by using a full-vector finite element method. The initial Yb^{3+}-doped PCF and tapered Yb^{3+}-doped PCF have been used to generate SC respectively, and the experimental results were analyzed. Owing to Yb^{3+} stimulated and radiated, a Ti:sapphire laser femtosecond pulse as pump source produces up conversion luminescence in the uniform and tapered Yb^{3+}-doped PCF. By pumping femtosecond pulse to the tapered Yb^{3+}-doped PCF, a wide violet peak of 388 nm to beyond 450 nm and an ultraflat spectrum with −7 dB output is obtained.

2. Low loss photonic crystal fiber taper

The characteristics of PCF prepared by linear fusion structure are studied. Fig. 1 is the tapered PCF structure diagram for the preparation of linear fusion taper.

In Fig. 1, the x-axis represents the radial direction of the optical fiber including the cone area, the z-axis shows the changes of the radius of the cross-section. R_0 is the radius of the optical fiber at the not-drawing cone, R_i is the radius of descending edge of the cone region, and R_w is the radius of the cone waist. L is the cone length of the whole cone region, including the descending edge, the cone waist and the cone region of rising edge. The $\alpha(x_1)$ is the cone angle of the fiber axis at the optical fiber axis to the x_1 (the cone is down at the beginning), the $\beta(x_2)$ is the cone angle of the fiber axis the fiber axis to the x_2, and y is any position in the descending edge cone region. The radius of the cladding of the tapered PCF in the cone region can be obtained by the linear geometric relationship, which can be denoted as

$$R_i(y) = R_0 - \frac{y}{L}(R_0 - R_w) \tag{1}$$

The structure of the air hole array in the doped with ytterbium PCF is hexagonal structure. The air hole spacing is Λ, and air hole radius is r. Under the condition of low loss drawing, geometric Λ and r are scaled. By Eq. (1), the cladding air hole radius r_j and the air hole spacing Λ_j of the descending edge cone region can be expressed as

$$r_j(y) = r_0 - \frac{y}{L}(r_0 - r_w) \tag{2}$$

$$\Lambda_j(y) = \Lambda_0 - \frac{y}{L}(\Lambda_0 - \Lambda_w) \tag{3}$$

where, r_0 is the air hole radius of not-drawing cone, r_j is the air hole radius of descending edge of cone, Λ_0 is the air hole spacing of not-drawing cone, and Λ_j is the air hole spacing of descending edge of cone.

Considering the fundamental mode in the cone area in the fiber core on propagation energy loss minimum gradient condition of fiber core pulling taper angle is less than the largest diffraction spread angle, the same low loss of cone gradient condition as well as the largest cone angle is less than the spread of the diffraction angle, that is

$$\alpha_{co}(x) < \alpha_{co-d}(x) \tag{4}$$

$$\beta_{cl}(x) < \beta_{cl-d}(x) \tag{5}$$